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THE ENERGY DEPENDENCE OF PROTON DAMAGE IN SILICON

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SPACE TECHNOLOGY LABORATORIES, INC.
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REDONDO BEACH, CALIFORNIA

REVISION OF

CHARGED PARTICLE RADIATION DAMAGE IN SEMICONDUCTORS, III: THE ENERGY DEPENDENCE OF PROTON DAMAGE IN SILICON

by

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I. INTRODUCTION

In a previous report[1], henceforth designated as A, theoretical calculations were made to determine the radiation damage in silicon due to high energy protons (10 Mev $\leq E_p \leq$ 2000 Mev). Since that time, more detailed calculations, involving refinements in some of the theoretical expressions and the inclusion of some additional "second-order" effects, have modified slightly the results quoted in A. These changes will not be described in detail.

As described in A, the spallation mechanism between an incident proton and a silicon target nucleus is a two-stage phenomenon, first involving a cascade interaction, followed by an evaporation stage. In A, it was assumed that the target nucleus, after recoiling from the cascade interaction with an energy E_{RN}, emitted isotropically a number of nucleons in the evaporation stage, before slowing to rest by collisons with atoms in the silicon lattice. In calculating the defect density due to this recoiling nucleus by Equation (8) of A, account was taken of both the fast nucleons M_{FP} and M_{FN} lost in the cascade, and the slow nucleons M_{SP} and M_{SN} emitted in the evaporation. However, it was assumed that the energy of the recoil nucleus, E_{RN}, was not changed during the evaporation process.

In the present paper, we shall describe the changes in the defect density due to the following two modifications: (1) a more detailed and accurate calculation, using the theory of LeCouteur[2], of the number of slow nucleons emitted; and (2) a calculation of the change in E_{RN} during the evaporation, a phenomenon previously neglected.

II. NUMBER OF SLOW NUCLEONS EMITTED

During the evaporation stage, the recoil nucleus, with excitation E^*, de-excites by the isotropic emission of nucleons and other lightweight particles ($A \leq 4$). We neglect all these particles except the nucleons ($A = 1$). In A, average values were assumed for the energies e_p and e_n carried off in the emissions of protons and neutrons, respectively. Thus, for a given initial E^*, it was possible to calculate M_{SP} and M_{SN}. A more detailed analysis, however, shows that e_p and e_n increase with increasing

E^*, so that the use of average values may lead to erroneous results. In the new calculation, a step-by-step analysis of the evaporation was made, beginning with an initial excitation energy E^*, and continuing until enough nucleons had been emitted to reduce E^* to about 7 Mev, below which no further nucleon emission is possible. For each step in the emission process, the actual e_p or e_n for that E^* was calculated, rather than using an average value as in paper A. Figure 1 shows the difference produced by the two methods. The graph shows the total number of slow nucleons, $M_S = M_{SP} + M_{SN}$, as a function of the incident proton energy E_p. It is seen that the more accurate analysis leads to smaller values of M_S than the earlier calculations. This in turn increases the defect density ρ_i due to the recoiling nucleus, as is obvious from Figure 1 of A. If M_S is smaller, then (Z_1, A_1) are larger, and for a given E, the value of $\nu(E)$ increases. Since ρ_i is directly proportional to $\nu(E)$ by Equations (7) and (8) of A, then ρ_i also increases if M_S decreases.

III. CHANGE OF RECOIL ENERGY E_{RN} IN EVAPORATION

In the previous paper, the increase in the recoil energy of the target nucleus, due to the emission of evaporated nucleons, was neglected for the following reason. From Figure 1 of A, it will be noted that in the energy range of interest (0.5 Mev $\leq E \leq$ 20 Mev), a 100 per cent change in E makes no more than about a 20 per cent change in $\nu(E)$, which is smaller than some of the other errors in $\nu(E)$, such as that discussed in Section II above. However, now that the larger error (in M_S) has been corrected, the error in E_{RN} was also removed.

Let us consider the momentum balance in the emission of a nucleon. Letting P_i and P_f be the initial and final momenta of the nucleus, which initially has mass number A, and P_o be the momentum of the emitted nucleon, then:

$$\underline{P}_f = \underline{P}_i - \underline{P}_o \qquad (1)$$

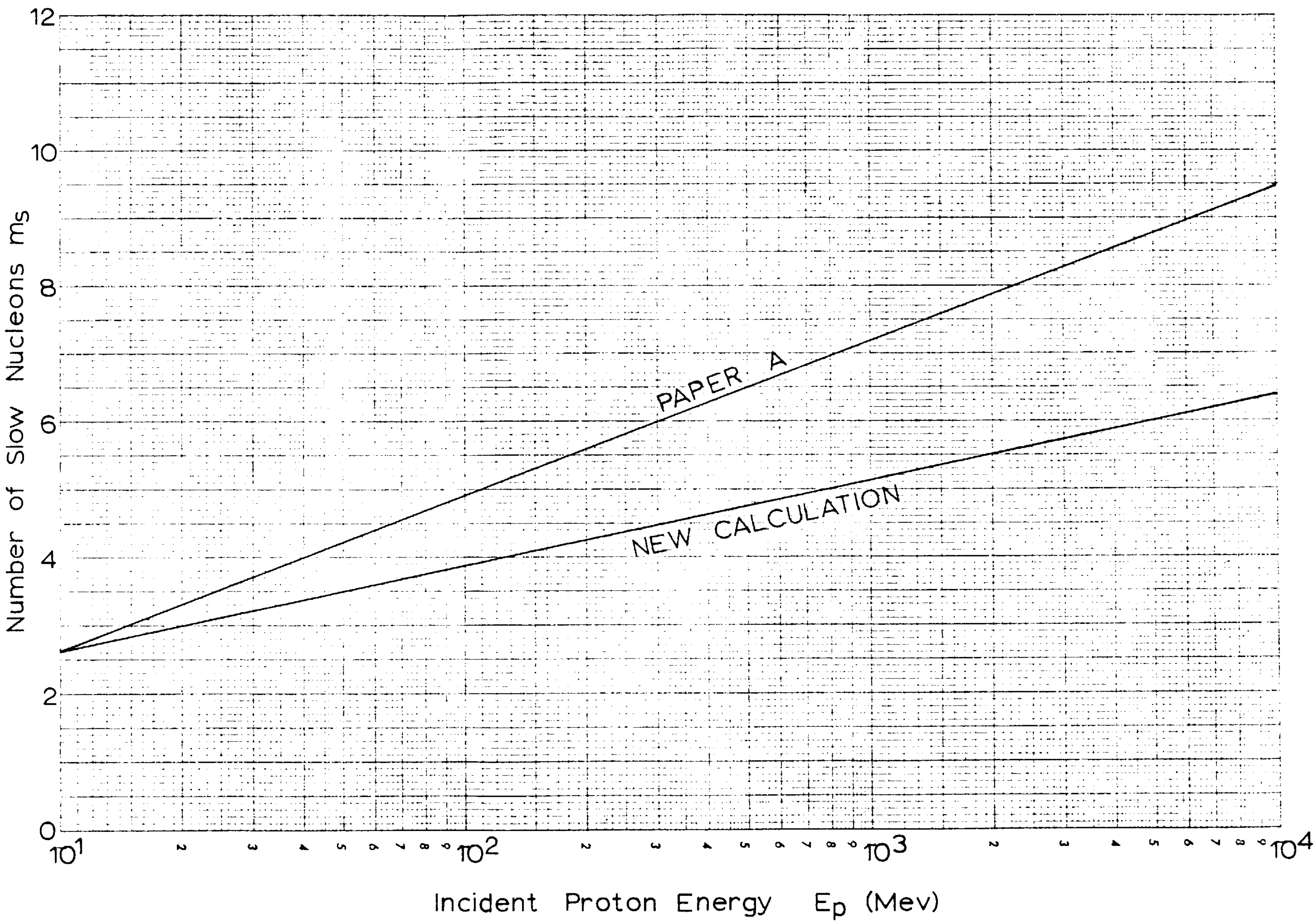

Figure 1. Number of Slow Nucleons Emitted by Excited Nucelus During Evaporation Stage

Taking the scalar product $\underline{P}_f \cdot \underline{P}_f$ we obtain:

$$P_f^{\,2} = P_i^{\,2} + P_o^{\,2} - 2\,(\underline{P}_i \cdot \underline{P}_o) \tag{2}$$

Under the assumption that the nucleons are evaporated isotropically, it follows that <u>on the average</u> we can write:

$$(\underline{P}_i \cdot \underline{P}_o)_{Ave} = 0 \tag{3}$$

For nonrelativistic energies, $E = P^2/2m$, so that (2) becomes:

$$2\,(A-1)\,E_f^{RN} = 2AE_i^{RN} + 2E_o \tag{4}$$

where E_o is either the calculated value e_p or e_n, depending on whether a proton or a neutron was emitted in this step. Thus, we obtain finally:

$$E_{i+1}^{RN} = \frac{A_i E_i + E_o}{A_i - 1} \tag{5}$$

for the energy of the recoil nucleus after emission of the ith nucleon. Figure 2 shows the increase in E_{RN} over the previous value. The average increase is approximately 60 to 70 per cent, and this produces roughly a 10 per cent increase in $\nu(E)$.

IV. <u>EFFECT OF CHANGES ON DEFECT DENSITY</u>

The combined effect of changes in M_S and E_{RN} was calculated from Figure 1 of A, and the corresponding change in Figure 2 of A was obtained. Figure 3 contains both the old values of the defect density (ρ_t, ρ_e, ρ_i) versus proton energy E_p as shown in Figure 2 of A, and also the new values of ρ_t and ρ_i from the present calculations.

It can be seen that the increase in ρ_i is 15 to 50 per cent while the corresponding change in ρ_t is 10 to 25 per cent. The resulting change in

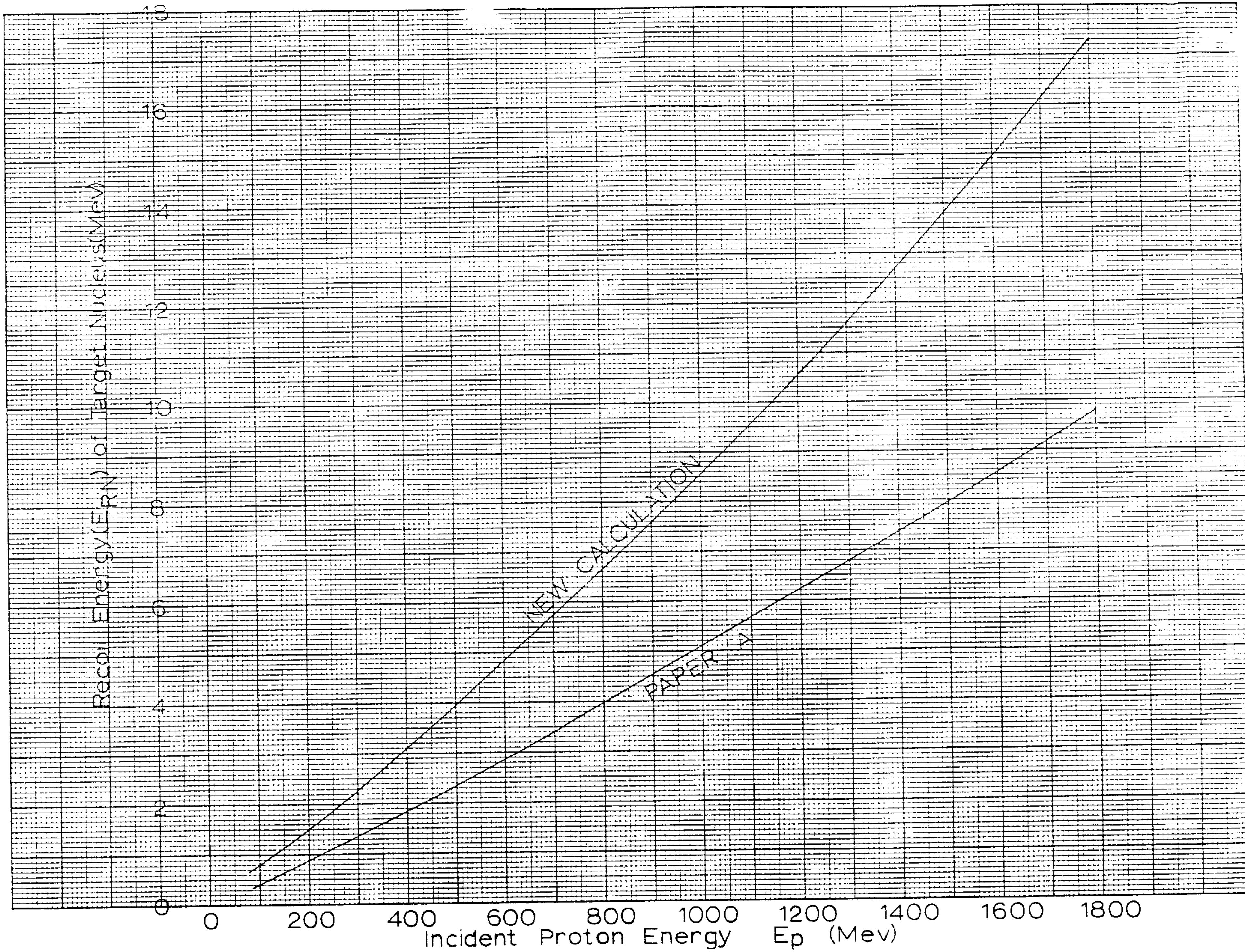

Figure 2. Recoil Energy of Target Nucleus Due to a High Energy Proton Bombardment

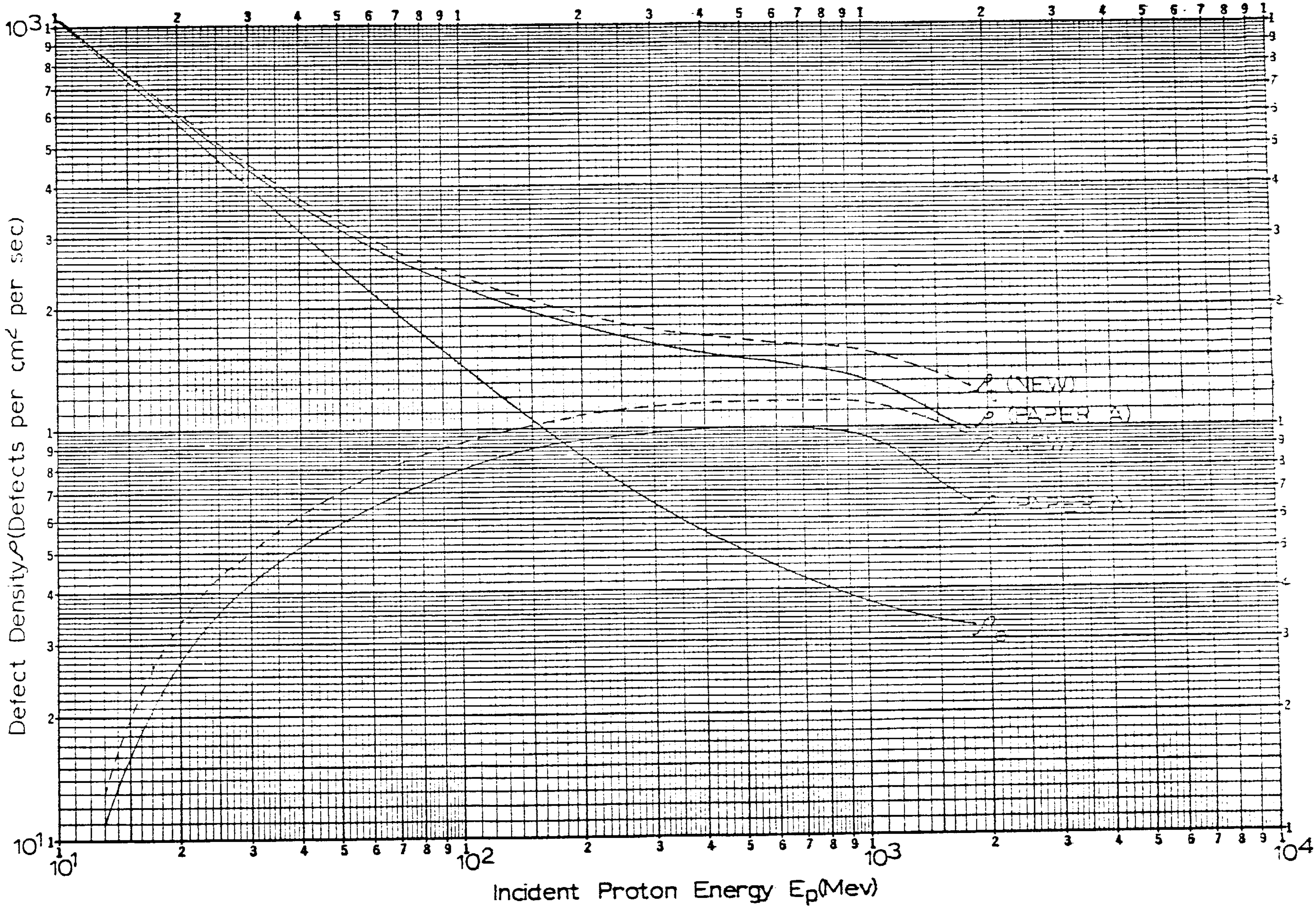

Figure 3. Calculated Defect Density in Silicon Due to High Energy Protons

the ratio ρ_t (95.5 Mev)/ρ_t (450 Mev) of Table I, Paper A, is from 1.53 to 1.48.

These results have been incorporated in the article submitted by the authors for publication in the Physical Review, to be published in March, 1963.

V. DISCUSSION

Although the absolute value of the defect density has been changed somewhat by the present calculations, the general shape of the defect density versus energy curves has not been altered.

In addition, the greatest uncertainty in the computation of the defect density has unfortunately not been resolved by these revised calculations; that is, the relative importance and different consequences of isolated point defects versus defect "clumps" or "spikes". Further theoretical calculations will be directed toward the solution of this difficult problem.

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1. J. M. Denney, R. G. Downing, G. W. Simon, "Charged Particle Radiation Damage in Semiconductors, III: The Energy Dependence of Proton Damage in Silicon," Contract No. NAS5-1851, 8653-6005-KU-000, 4 October 1962 (referred to as A in the present paper).

2. K. J. LeCouteur, Proceedings of Physical Society (London), 63A, 259 (1950).